

Lasso Regression

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Lasso Regression

- LASSO \rightarrow Least absolute shrinkage and selection operator
- Popular as it leads to a sparse solution.

Constructing the Objective Function

- Find a θ_{opt} such that

$$\theta_{\text{opt}} = \arg \min_{\theta} (\mathbf{y} - \mathbf{X}\theta)^T (\mathbf{y} - \mathbf{X}\theta) : \|\theta\|_1 < s \quad (1)$$

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$$\theta_{\text{opt}} = \arg \min_{\theta} (\mathbf{y} - \mathbf{X}\theta)^T (\mathbf{y} - \mathbf{X}\theta) : \|\theta\|_1 < s \quad (1)$$

- Using KKT conditions

$$\theta_{\text{opt}} = \arg \min_{\theta} \underbrace{(\mathbf{y} - \mathbf{X}\theta)^T (\mathbf{y} - \mathbf{X}\theta) + \delta^2 \|\theta\|_1}_{\text{convex function}} \quad (2)$$

Solving the Objective

- Since $\|\boldsymbol{\theta}\|_1$ is not differentiable, we cannot solve,

$$\frac{\partial(\mathbf{y} - \mathbf{X}\boldsymbol{\theta})^T(\mathbf{y} - \mathbf{X}\boldsymbol{\theta}) + \delta^2\|\boldsymbol{\theta}\|_1}{\partial\boldsymbol{\theta}} = 0 \quad (3)$$

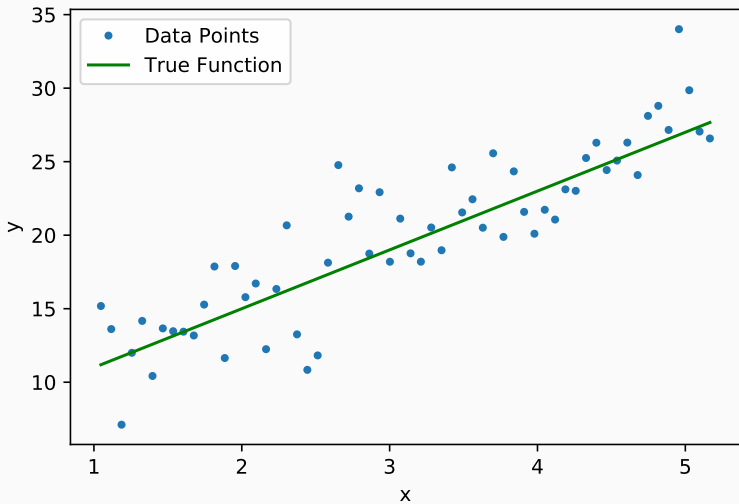
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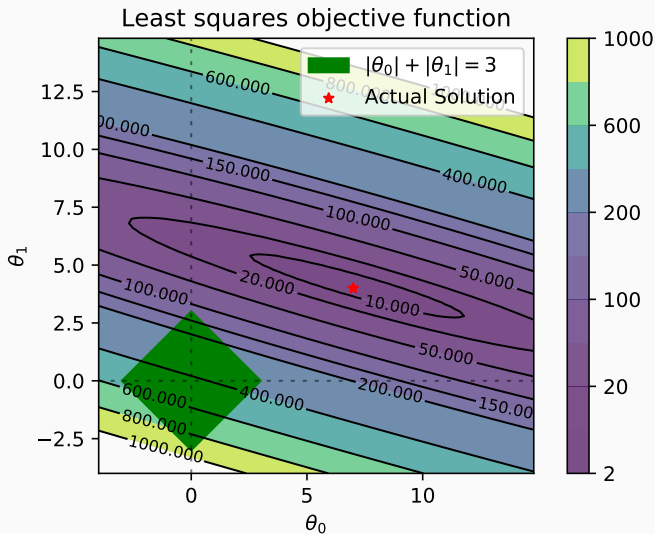
- How to Solve? Use coordinate descent!

Sample Dataset



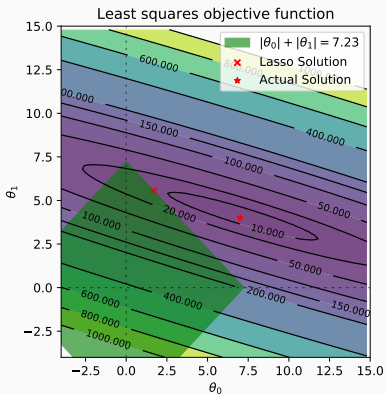
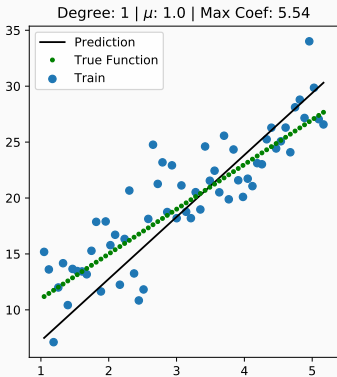
$$y = 4x + 7$$

Geometric Interpretation



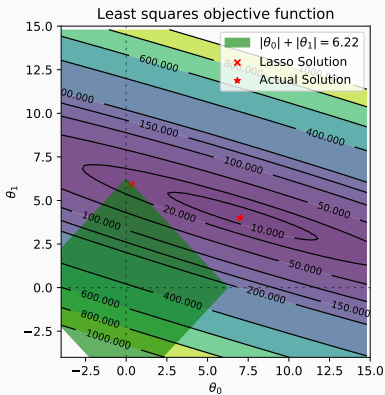
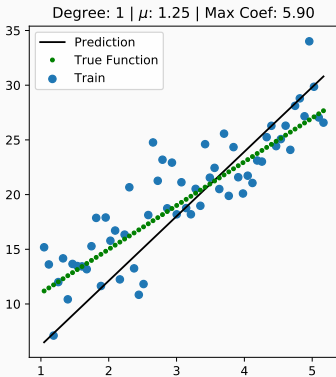
Lasso regression

Effect of μ - Regularization of Parameters



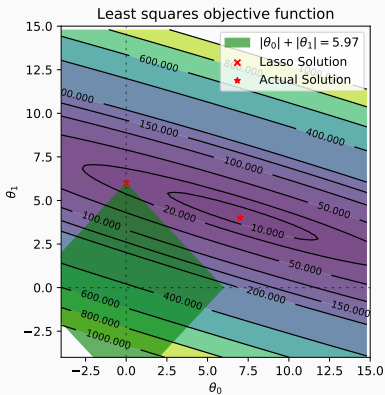
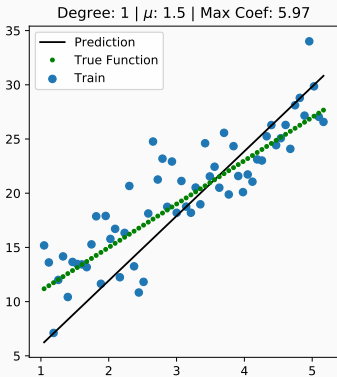
$\mu = 1.0$
(on the *Sample Dataset*)

Effect of μ - Regularization of Parameters



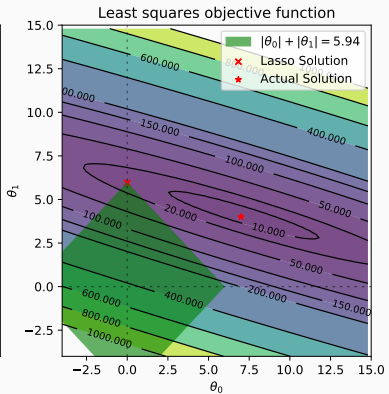
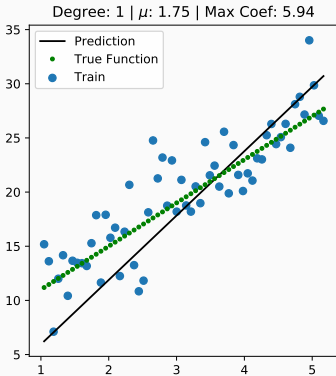
$\mu = 1.25$
(on the *Sample Dataset*)

Effect of μ - Regularization of Parameters



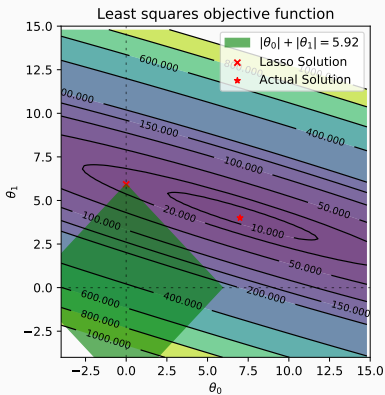
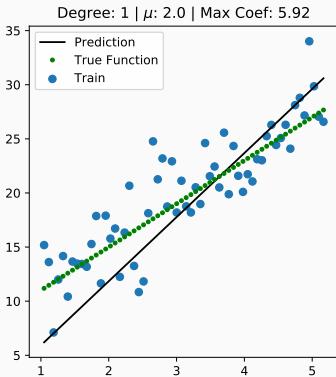
$\mu = 1.5$
(on the *Sample Dataset*)

Effect of μ - Regularization of Parameters



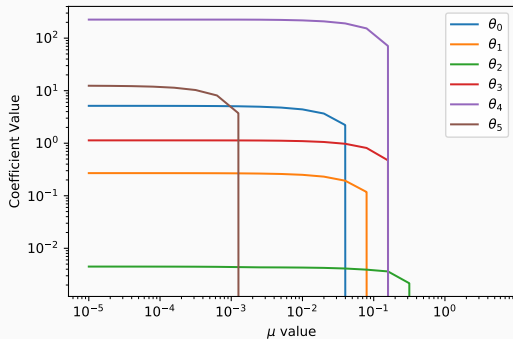
$\mu = 1.75$
(on the *Sample Dataset*)

Effect of μ - Regularization of Parameters



$\mu = 2.0$
(on the *Sample Dataset*)

Regularization path of lasso regression



Regularization path of θ_i

- LASSO inherently does feature selection!

LASSO and feature selection

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- Sets coefficients of “less important” features to zero.

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- Sets coefficients of “less important” features to zero.
- Sparse and memory efficient and often more interpretable models.

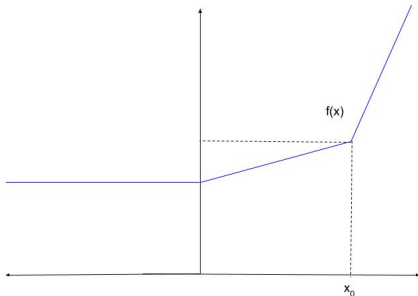
- Generalises gradient to convex but non-differentiable problems

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- Examples:

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- Examples:
 - $f(x) = |x|$

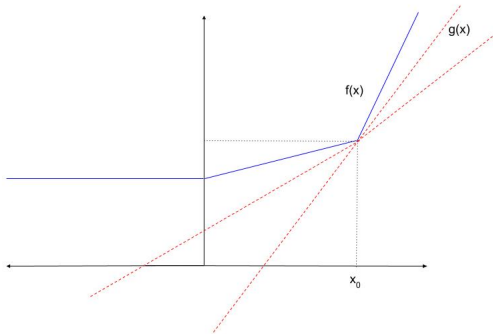
Task at hand

- TASK: find derivative of $f(x)$ at $x = x_0$



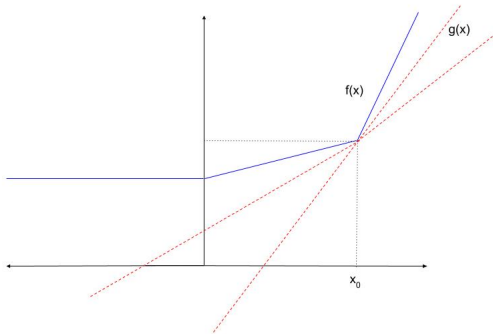
Solution

- Construct a differentiable $g(x)$



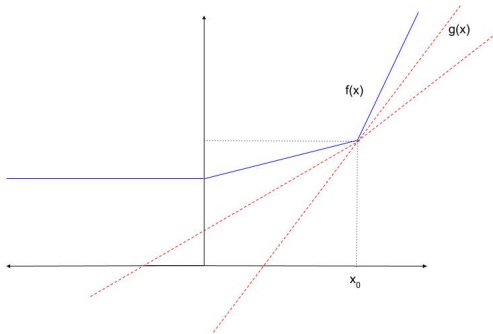
Solution

- Construct a differentiable $g(x)$
 - Intersecting $f(x)$ at $x = x_0$



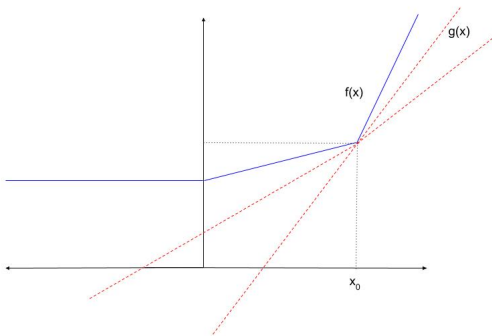
Solution

- Construct a differentiable $g(x)$
 - Intersecting $f(x)$ at $x = x_0$
 - Below or on $f(x)$ for all x



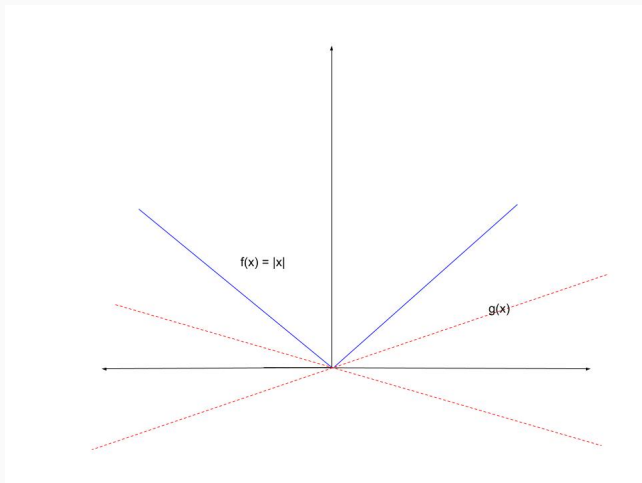
Solution

- Compute slope of $g(x)$ at $x = x_0$



Another Example: $f(x) = |x|$

- Subgradient of $f(x)$ belongs to $[-1, 1]$



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Coordinate Descent

- Another optimisation method (akin to gradient descent)
- Objective: $\min_{\theta} f(\theta)$
- Key idea: Sometimes difficult to find minimum for all coordinates
- ..., but, easy for each coordinate
- turns into a one-dimensional optimisation problem

- Picking next coordinate:

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- Picking next coordinate: random, round-robin
- No step-size to choose!

Coordinate Descent

- Picking next coordinate: random, round-robin
- No step-size to choose!
- Converges for Lasso objective

Coordinate Descent : Example

Learn $y = \theta_0 + \theta_1 x$ on following dataset, using coordinate descent where initially $(\theta_0, \theta_1) = (2, 3)$ for 2 iterations.

x	y
1	1
2	2
3	3

Coordinate Descent : Example

Our predictor, $\hat{y} = \theta_0 + \theta_1 x$

Error for i^{th} datapoint, $\epsilon_i = y_i - \hat{y}_i$

$$\epsilon_1 = 1 - \theta_0 - \theta_1$$

$$\epsilon_2 = 2 - \theta_0 - 2\theta_1$$

$$\epsilon_3 = 3 - \theta_0 - 3\theta_1$$

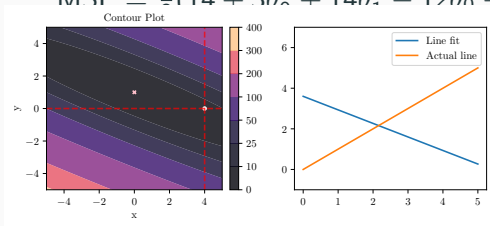
$$\text{MSE} = \frac{\epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2}{3} = \frac{14 + 3\theta_0^2 + 14\theta_1^2 - 12\theta_0 - 28\theta_1 + 12\theta_0\theta_1}{3}$$

Iteration 0

$$\text{MSE} = \frac{1}{3}(14 + 3\theta_0^2 + 14\theta_1^2 - 12\theta_0 - 28\theta_1 + 12\theta_0\theta_1)$$

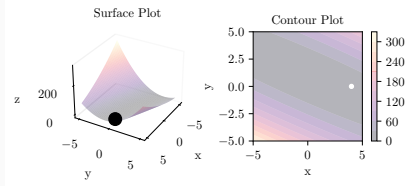
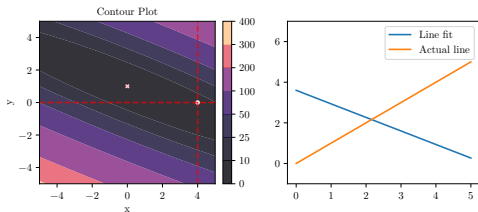
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Coordinate Descent : Example

Iteration 1

INIT: $\theta_0 = 2$ and $\theta_1 = 3$

$\theta_1 = 3$ optimize for θ_0

Coordinate Descent : Example

Iteration 1

INIT: $\theta_0 = 2$ and $\theta_1 = 3$

$\theta_1 = 3$ optimize for θ_0

$$\frac{\partial \text{MSE}}{\partial \theta_0} = 6\theta_0 + 24 = 0$$

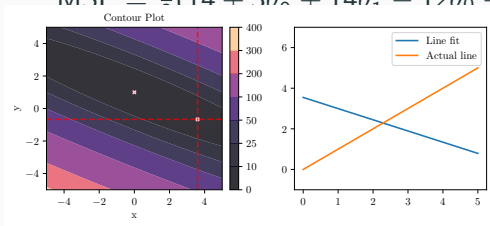
$$\theta_0 = -4$$

Iteration 1

$$\text{MSE} = \frac{1}{3}(14 + 3\theta_0^2 + 14\theta_1^2 - 12\theta_0 - 28\theta_1 + 12\theta_0\theta_1)$$

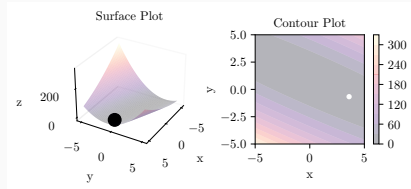
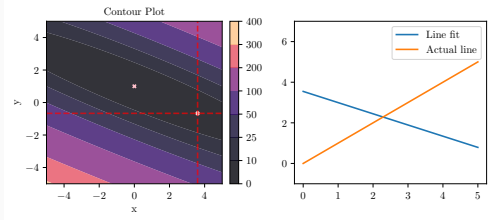
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Coordinate Descent : Example

Iteration 2

INIT: $\theta_0 = -4$ and $\theta_1 = 3$

$\theta_0 = -4$ optimize for θ_1

Coordinate Descent : Example

Iteration 2

INIT: $\theta_0 = -4$ and $\theta_1 = 3$

$\theta_0 = -4$ optimize for θ_1

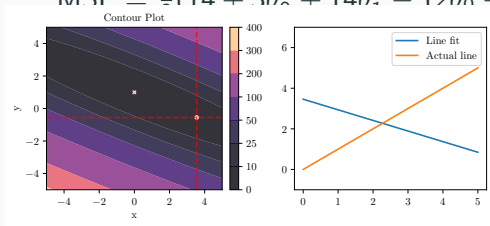
$\theta_1 = 2.7$

Iteration 2

$$\text{MSE} = \frac{1}{3}(14 + 3\theta_0^2 + 14\theta_1^2 - 12\theta_0 - 28\theta_1 + 12\theta_0\theta_1)$$

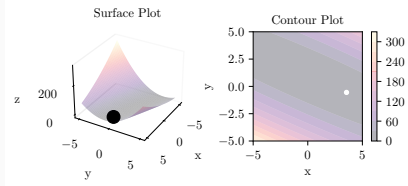
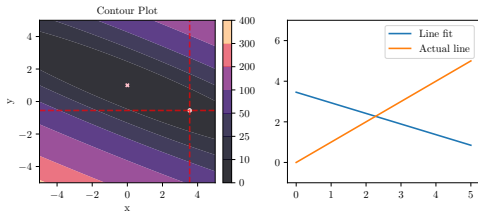
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Coordinate Descent : Example

Iteration 3

INIT: $\theta_0 = -4$ and $\theta_1 = 2.7$

$\theta_1 = 2.7$ optimize for θ_0

Coordinate Descent : Example

Iteration 3

INIT: $\theta_0 = -4$ and $\theta_1 = 2.7$

$\theta_1 = 2.7$ optimize for θ_0

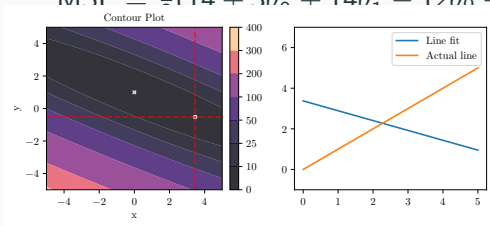
$\theta_0 = -3.4$

Iteration 3

$$\text{MSE} = \frac{1}{3}(14 + 3\theta_0^2 + 14\theta_1^2 - 12\theta_0 - 28\theta_1 + 12\theta_0\theta_1)$$

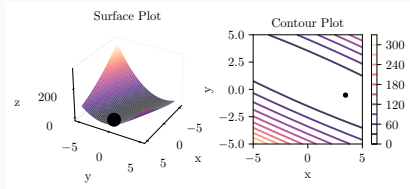
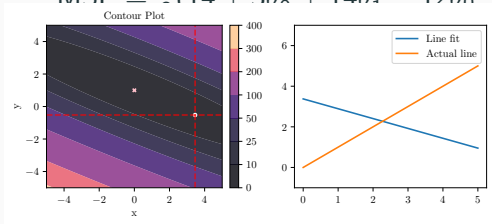
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Coordinate Descent for Unregularised Regression

- Express error as a difference of y_i and \hat{y}_i

$$\hat{y}_i = \sum_{j=0}^d \theta_j x_i^j = \theta_0 x_i^0 + \theta_1 x_i^1 + \theta_2 x_i^2 + \dots + \theta_d x_i^d \quad (4)$$

$$\epsilon_i = y_i - \hat{y}_i = y_i - \theta_0 x_i^0 - \theta_1 x_i^1 - \dots - \theta_d x_i^d = y_i - \sum_{j=0}^d \theta_j x_i^j \quad (5)$$

Coordinate Descent for Unregularised regression

$$\sum_{i=1}^n \epsilon^2 = \text{RSS} = \sum_{i=1}^n \left(y_i - \left(\theta_0 x_i^0 + \dots + \theta_j x_i^j + \theta_d x_i^d \right) \right)^2$$

Coordinate Descent for Unregularised regression

$$\sum_{i=1}^n \epsilon^2 = \text{RSS} = \sum_{i=1}^n \left(y_i - \left(\theta_0 x_i^0 + \dots + \theta_j x_i^j + \theta_d x_i^d \right) \right)^2$$
$$\frac{\partial \text{RSS}(\theta_j)}{\partial \theta_j} = 2 \sum_{i=1}^n \left(y_i - \left(\theta_0 x_i^0 + \dots + \theta_j x_i^j + \dots \right) \right) \left(-x_i^j \right)$$

Coordinate Descent for Unregularised regression

$$\begin{aligned}\sum_{i=1}^n \epsilon^2 &= \text{RSS} = \sum_{i=1}^n \left(y_i - \left(\theta_0 x_i^0 + \dots + \theta_j x_i^j + \theta_d x_i^d \right) \right)^2 \\ \frac{\partial \text{RSS}(\theta_j)}{\partial \theta_j} &= 2 \sum_{i=1}^n \left(y_i - \left(\theta_0 x_i^0 + \dots + \theta_j x_i^j + \dots \right) \right) \left(-x_i^j \right) \\ &= 2 \sum_{i=1}^n \left(y_i - \left(\theta_0 x_i^0 + \dots + \theta_d x_i^d \right) \right) \left(-x_i^j \right) + 2 \sum_{i=1}^n \theta_j (x_i^j)^2\end{aligned}$$

Coordinate Descent for Unregularised regression

$$\begin{aligned}\sum_{i=1}^n \epsilon^2 &= \text{RSS} = \sum_{i=1}^n \left(y_i - \left(\theta_0 x_i^0 + \dots + \theta_j x_i^j + \theta_d x_i^d \right) \right)^2 \\ \frac{\partial \text{RSS}(\theta_j)}{\partial \theta_j} &= 2 \sum_{i=1}^n \left(y_i - \left(\theta_0 x_i^0 + \dots + \theta_j x_i^j + \dots \right) \right) \left(-x_i^j \right) \\ &= 2 \sum_{i=1}^n \left(y_i - \left(\theta_0 x_i^0 + \dots + \theta_d x_i^d \right) \right) \left(-x_i^j \right) + 2 \sum_{i=1}^n \theta_j (x_i^j)^2\end{aligned}$$

where:

$$\hat{y}_i^{(-j)} = \theta_0 x_i^0 + \dots + \theta_d x_i^d$$

is \hat{y}_i without θ_j

Coordinate Descent for Unregularised regression

$$\text{Set } \frac{\partial \text{RSS}(\theta_j)}{\partial \theta_j} = 0$$

$$\theta_j = \sum_{i=1}^n \frac{(y_i - (\theta_0 x_i^0 + \dots + \theta_d x_i^d)) (x_i^j)}{(x_i^j)^2} = \frac{\rho_j}{z_j}$$

$$\rho_j = \sum_{i=1}^n x_i^j (y_i - \hat{y}_i^{(-j)}) \quad \text{and} \quad z_j = \sum_{i=1}^n (x_i^j)^2$$

z_j is the squared of ℓ_2 norm of the j^{th} feature

Coordinate Descent for Lasso Regression

$$\text{Minimise } \underbrace{\sum_{i=1}^n \epsilon^2 + \delta^2 \{|\theta_0| + |\theta_1| + \dots |\theta_j| + \dots |\theta_d|\}}_{\text{LASSO OBJECTIVE}}$$

$$\frac{\partial}{\partial \theta_j} (\text{LASSO OBJECTIVE}) = -2\rho_j + 2\theta_j z_j + \delta^2 \frac{\partial}{\partial \theta_j} |\theta_j|$$

$$\frac{\partial}{\partial \theta_j} |\theta_j| = \begin{cases} 1 & \theta_j > 0 \\ [-1, 1] & \theta_j = 0 \\ -1 & \theta_j < 0 \end{cases}$$

Coordinate Descent for Lasso Regression

- **Case 1:** $\theta_j > 0$

$$-2\rho_j + 2\theta_j z_j + \delta^2 = 0$$

$$\theta_j = \frac{\rho_j - \frac{\delta^2}{2}}{z_j}$$

$$\rho_j > \frac{\delta^2}{2} \Rightarrow \theta_j = \frac{\rho_j - \frac{\delta^2}{2}}{z_j}$$

Coordinate Descent for Lasso Regression

- **Case 1:** $\theta_j > 0$

$$-2\rho_j + 2\theta_j z_j + \delta^2 = 0$$

$$\theta_j = \frac{\rho_j - \frac{\delta^2}{2}}{z_j}$$

$$\rho_j > \frac{\delta^2}{2} \Rightarrow \theta_j = \frac{\rho_j - \frac{\delta^2}{2}}{z_j}$$

- **Case 2:** $\theta_j < 0$

$$\rho_j < \frac{\delta^2}{2} \Rightarrow \theta_j = \frac{\rho_j + \delta^2/2}{z_j} \tag{6}$$

Coordinate Descent for Lasso Regression

- **Case 3:** $\theta_j = 0$

$$\frac{\partial}{\partial \theta_j}(\text{LASSO OBJECTIVE}) = -2\rho_j + 2\theta_j z_j + \delta^2 \underbrace{\frac{\partial}{\partial \theta_j} |\theta_j|}_{[-1,1]}$$

$$\in \underbrace{[-2\rho_j - \delta^2, -2\rho_j + \delta^2]}_{\{0\} \text{ lies in this range}}$$

$$-2\rho_j - \delta^2 \leq 0 \text{ and } -2\rho_j + \delta^2 \geq 0$$

$$-\frac{\delta^2}{2} \leq \rho_j \leq \frac{\delta^2}{2} \Rightarrow \theta_j = 0$$

Summary of Lasso Regression

$$\theta_j = \begin{bmatrix} \frac{\rho_j + \frac{\delta^2}{2}}{z_j} & \text{if } \rho_j < -\frac{\delta^2}{2} \\ 0 & \text{if } -\frac{\delta^2}{2} \leq \rho_j \leq \frac{\delta^2}{2} \\ \frac{\rho_j - \frac{\delta^2}{2}}{z_j} & \text{if } \rho_j > \frac{\delta^2}{2} \end{bmatrix} \quad (7)$$